PROTON BUNCHING OPTIONS *

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Muon Colliders[1] need intense, very short, proton bunches. The requirements are presented and a number of possible bunching systems discussed. The best solution uses a small super-conducting buncher ring with 6 bunches that are taken though separate transports and combined on the target.

Keywords: Muon Collider; proton driver; space charge tune shift

1. introduction

Because a collider luminosity depends on the square of the bunch charges, intense bunches of 2 10^{12} muons are required. To generate such bunches requires intense proton bunches. Fig.1 shows the relative muon fluxes predicted by MARS15[2] vs. the proton energy used to make them. The muons counted were from a full simulation[3] of the front end of a neutrino factory including ICOOL[?] simulation of pion capture, pion decay to muons, phase rotation of the muons, and 80 m of transverse cooling. The muons selected were within acceptances of 30 mm transverse and 150 mm longitudinal. It is seen that there is a strong advantage in using protons of around 8 GeV. But at this energy, the required numbers of protons is ($approx 200$ 10^{12}, and space charge tune shift when they are compressed to the required bunch length of 2 ns are serious.

Space Charge Tune Shift[4] is given by

$$\Delta\nu \;=\; F_{dist}\;\left(\frac{2\pi R}{\sqrt{2\pi}\;\sigma_z}\right)\;\frac{N_p\;r_o}{2\pi\;\epsilon_N\;\beta_v\gamma^2}$$

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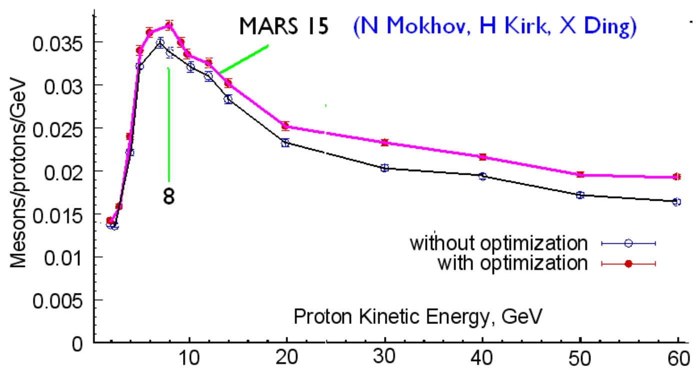

Fig. 1. Relative pion production vs. proton energy.

$$\Delta\nu = F_{dist} \left(\frac{2\pi R}{\sqrt{2\pi}\ \sigma_z}\right) \frac{N_p\ r_o}{2\pi\ \epsilon_N\ \beta_v\gamma^2}$$

For Gaussian beams $F_{dist} = 3.8$, where ϵ_N is the normalized (95%) emittance as used for protons at FNAL, and $\epsilon_\perp = \epsilon_N/6$ is the rms normalized emittance as used in Muon Collider studies.

The ring circumference is $C = 2\pi R$ so

$$\Delta\nu = 0.63 \left(\frac{C}{\sqrt{2\pi}\ \sigma_z}\right) \frac{N_p\ r_o}{2\pi\ \epsilon_\perp\ \beta_v\gamma^2}$$

2. Six buncher cases considered

The above formula is now applied to a number of numbered cases with parameters given in Tb.**??**.

(1) FNAL Booster at 400 MeV injection energy yields a tune shift of 0.4, as published[5]
(2) A booster-like ring bunching 200 10^{12} protons to 2 ns at 8 GeV. Assuming the same geometrical emittance of the FNAL booster at injection: the 95% normalized emittance is 112 μm, and the space charge tune shift is 5.1 which is not viable.
(3) A ring using super-conducting magnets with fields of 4-5T instead of the booster's 1T. Its circumference would be much less: $\approx$ 200 m instead of 474 m. A 95% emittance of 200 is now assumed (rms $\epsilon_\perp = 33$). The tune shift is reduced to 1.2, but this is still not viable.

Table 1. Parameters of bunchers

		1 Booster at inj	2 Booster at 8 GeV	3 SC	4 24 GeV	5 FFAG	6 6 bunch
E	GeV	0.4	8	8	24	8	8
Circ	m	474	474	200	561	339	200
N_p	10^{12}	0.06	200	200	96	200	200/6
σ_z	m	1.5	.66	.66	.66	.66	.66
σ_θ	m	1.2	1.2	2.1	0.7	21	2.1
ϵ_N	μm	12	112	200	200	2000	200
$\epsilon_\perp$	(μm	2	33	33	33	330	33
nb		84	1	1	1	1	6
$\Delta\nu$		0.4	5.1	1.2	0.21	0.21	0.2

(4) A solution would be to use higher energy protons (e.g. 24 GeV). Assuming the same buncher ring acceptance and average bending field as in cases #s 3 & 4, then from Fig.1 the needed proton bunch intensity is 96 10^{12} and the tune shift for one bunch is a reasonable 0.21. But because pion production per GeV is now less, the required proton power is a factor of ≈2 higher.

(5) Instead of using multiple bunches one might try using a very large acceptance ring, such as the 5-10 GeV FFAG designed for muon acceleration in Study 2a.[7] That ring has a 339 m circumference and a normalized muon acceptance of 30 mm. With an rms emittance =1/10 of this, the normalized proton emittance $\epsilon_\perp = 3000\times\ 106/970 = 330$ mm. The tune shift with one bunch is now a reasonable 0.21, but when this huge emittance is focused down to 1/3 of the 5 mm target radius, the 3 sigma angular spread is 3 σ_θ = 63 mrad: $\approx\ 2\times$ the crossing angle between the beam and jet. This is not viable.

(6) With the same ring, but with the charge distributed in 6 bunches the tune shift is down to an acceptable 0.2. The bunches can be extracted into transports of differing lengths (trombones as in Fig.2a)[6] to bring them all onto the target at the same time. Since the beam intersects the mercury jet target from the side at an angle ≈ 33 mrad, so it should be ok to bring multiple beams in from multiple azimuths, all at the same angle to the jet, see Fig.2b. It is seen that the three sigma sizes of the separate beams are well separated.

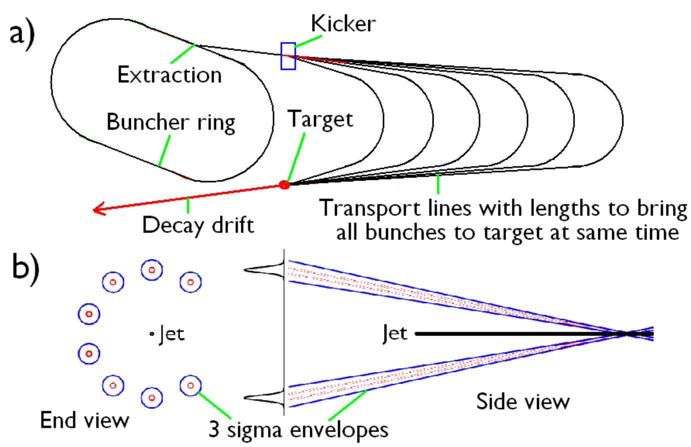

Fig. 2. a)Trombone transport lines to bring all bunches to the target at the same time; b)Multiple beam target geometry

3. Conclusion

Pion, and thus muon, production is predicted to have a maximum for 8 GeV protons. The muon collider then requires 200 10^{12} protons/bunche with $\sigma_t \approx 2$ ns. The space charge tune shifts of such bunches in an FNAL Booster ring is excessive. The space charge is reduced if higher bending fields allow a smaller circumference ring (474→200 m), and if the acceptance is increased $\approx 1.8\times$, and the charge is divided into 6 bunches, then the tune shift is an acceptable (≈ 0.2). An FFAG-like ring with its huge acceptance is ok for tune shift, but makes too large a beam on target. Tune shift & beam size are also ok for single bunches in super-conducting rings at 24 GeV or above, but MARS15 predicts a need for $\approx 1.7\times$the proton power

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